Performance Analysis of the Developmental Cryogenic Active Telescope Testbed (DCATT)

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ABSTRACT

Various efforts are underway to demonstrate hardware for the Next Generation Space Telescope (NGST). One such effort is the development of the DCATT testbed. This testbed is an NGST effort geared to demonstrating in hardware the end-to-end system functionality. The system includes a segmented telescope, active optics subsystem with a deformable mirror (DM), and a wavefront sensor. The degree to which the DCATT can demonstrate this functionality depends crucially on its performance. A system performance analysis of this testbed is presented. The analysis is based on the design of the DCATT developed by Goddard and JPL. In the analysis, the performance of the system as a function of key system factors is calculated. These factors include the following: control, environmental, fabrication, alignment, and design. The performance after correction by the DM is required to be diffraction-limited at a wavelength of 2.0 microns. The flowdown of this performance is called the corrected error budget. To fully characterize the testbed performance as a system, one must develop a budget for the performance of the system before action of the DM. The flowdown of this performance is called the uncorrected error budget. The top line of this budget is related to the correction capability of the DM.

Keywords: NGST, Active Optics, Adaptive Optics, Deformable Mirror, Error Budget

1. INTRODUCTION

The DCATT is one of the technology efforts under the NGST program. These technology efforts are described in another paper[1]. DCATT is intended to demonstrate, in hardware, the major funtionality of the NGST system. The program to accomplish this mission is described elsewhere[2]. The purpose of this paper is to analyze the predicted performance of the testbed in carrying out the vital function of wavefront control. The performance of the wavefront control subsystem, before operation of the DM but after initial alignment and coarse control, will be analyzed. Then the performance will be analyzed after operation of the DM. The performance of the system is described as a function of the following crucial factors: control, environmental, fabrication, alignment, and design.

Before describing details of the analysis, an overview of the system is first given. A display of the functional block diagram of the DCATT system is part of this overview. The wavefront control process is one of the functions shown. The physical configuration (layout) of the system is presented to provide physical clarity to the subsystems and components analyzed. A brief overview of the optical design is then given. More details of this design are elaborated in a separate paper[3]. Next the testbed operational phases are described briefly. The optomechanical controls of the telescope components are described.

Then the basis of the analysis is elaborated. The results before operation of the DM but after initial alignment and course control are presented in the uncorrected error budget. The results after operation of the DM are presented in the corrected error budget. Lastly the connection to the design sensitivity analysis is made. The fabrication specifications and alignment tolerances for the optical elements are developed by connecting the sensitivity analysis to the uncorrected error budget. Finally conclusions drawn from the analysis are presented.

2. OVERVIEW OF THE SYSTEM

The overall testbed layout is shown in Figure 1. It is a top view of the aft optics bench and an unfolded view of the telescope.

Figure 1. Layout of the unfolded system

For purposes of our analysis, the system is decomposed in the parts that would be present in an operational NGST. The main blocks are an input (analogous to light propagated from a distant source), light gathering module (a telescope) and an aft optics bench. The electronics and data processors/computers (encompassing all functions occurring after conversion of photons to electrons) are not the subject of analysis here. The aft optics (AO) bench encompasses four functions: sensor (CCD Camera), wavefront control (DM), beam position control (fast steering mirror and quad cell), and piston control (dispersed fringe sensor and segment actuator drives). Since this is a laboratory experiment, input in the DCATT system is not a distant star but rather a subsystem comprised of the source module, telescope on first pass, and auto-collimating (AC) flat. This analysis has been conducted assuming ambient operating temperatures for the entire system.

A steel base supported on six vibration isolation mounts provides the foundation for the telescope assembly and for the AO bench. The base will be located on an isolated granite slab in a cleanroom environment. The main components of the telescope assembly are a segmented parabolic primary mirror (PM), a hyperbolic secondary mirror (SM), six degree of freedom actuation systems (hexapods) for each

PM segment and the SM, a metering tower between the PM and the SM, and a 3-DOF AC flat. The AO bench contains the source module, a deformable mirror (DM), a fast steering mirror (FSM), and a translating CCD camera for phase retrieval (fine segment and DM alignment and phasing). The testbed will be surrounded by a shroud to block air currents and provide some acoustic damping.

The parabolic primary mirror design consists of a ring of six hexagonal segments arranged around a central hexagonal segment. The clear aperture of the parent f/2.2 primary mirror is 903 mm. The design goal for the telescope is to achieve diffraction limited imaging over a 2 arcminute field of view. The arrangement provides 6 independent degrees of freedom (DOF) for each segment in the primary and the secondary.

The Zerodur autocollimating flat will be mounted on a nine-point Hindle mount, which will in turn be mounted to a motorized jackscrew system having tip, tilt, and piston control. This mirror is tilted to cover the 4 arcmin field of view of the system. First order design parameters and more details on the telescope design can be found elsewhere[3]. The Source Module (SM) is located near the telescope focus and consists of a white light source and a 633 nanometer laser.

The Xinetics 349 actuator device selected utilizes PMN actuators having a 4-micron range of travel and 7 mm spacing. The telescope, which is the entrance pupil, is reimaged onto the DM. A Fast Steering Mirror (FSM) is planned for the system. The FSM requirements are still under investigation and its design is not complete. Its location is shown in the above figure. A quad cell will provide closed loop feedback to the FSM.

Coarse segment phasing will be accomplished using the dispersed fringe sensor (DFS), which can be rotated in and out of the optical path. The primary fine phasing and alignment wavefront sensing will utilize the CCD camera, which is mounted on a translation stage for focus and defocus images. These measurements will be used to evaluate the degree of wavefront correction, as well as the accuracy of different phase retrieval algorithms or other wavefront sensing approaches. More detailed information on the design and uses of the optics bench components can be found in the design paper[3].

Establishing DCATT as a viable operating testbed requires a two phase process. First initial installation and alignment of all the optics is required. (Component leveling testing and characterization is completed before this step). This first phase concludes with acquisition of light through the entire system and onto the camera (first light). The system is configured to test the telescope double pass plus AO bench optics single pass. The final closed loop operational sequence is described elsewhere[2].

The segments are of such a design with sufficient stiffness and rigidity, such that the resulting motions display a rigid body character, i.e. display no bending. Thus the baseline plan for DCATT does not include segment figure control. Segments may be developed later that exhibit such a feature. The analysis presented in this paper covers the conclusion of this last phase, in which operation of the DM is invoked. This operation and the associated control system is now analytically investigated .

3. BASIS OF THE ANALYSIS

In any control system the magnitude of the error signal to be rejected must be within the dynamic range of the control system. This error rejection capability of the system must be investigated and the residual error ascertained. This error must be smaller than the requirement or the system has not performed adequately. The requirement for the residual wavefront error for the DCATT System is to be diffraction limited, 1/14 wave root-mean–square (rms) at a 2 um wavelength. Most of the precision measurements are accomplished at wavelength of 632.8 nm. Scaled to this wavelength the requirement becomes 1 / 4.43 wave rms. These results must be achieved after the DM and its control system for DCATT have operated.

It is important to keep in mind what system compensators can be exercised. A compensator is an adjustment of one part of a system to reduce an error generated in another part of the system. For purposes of this analysis camera axial position (despace) can be adjusted and is such a compensator. Camera lateral position (decenter) is another. No others are used generally, but any other compensator used in a part of the analysis will be mentioned in that particular context.

The magnitude of the error signal to be rejected by the DM must now be investigated. Each actuator displacing the DM surface has a linear extension range of 4um, which is labeled S. Corresponding to this peak-to-valley (p-v) DM surface range S, the induced wavefront deformation is nearly 2S (normal incidence). The ratio between the p-v and rms is approximately 6 for wavefronts with relatively higher-order aberration content. Thus the wavefront RMS range is 2S/6 = S/3. If one-half of this range is selected as a suitable uncorrected wavefront, we arrive at an uncorrected RMS wavefront deformation of S/6. For S = 4um, the uncorrected RMS is very nearly one wave at 632.8nm. An ongoing modeling effort is attempting to better determine a suitable uncorrected value. In the interim, a goal of 1 wave at this wavelength is selected.

Thus the last phase of the optical control experiment for DCATT will feature the wavefront reconstruction (using phase retrieval) and DM actuation that takes a one wave rms (@632.8nm) wavefront and reduces it to 1 /4.43 waves rms. This modest requirement is mainly constrained by the DM range. As a goal it is desired to achieve a lower residual, perhaps even diffraction-limited (1 /14 wave)rms, at 632.8nm.

4. UNCORRECTED ERROR BUDGET

The top line of the error disturbance, to be rejected by the DM, has been determined to be one wave rms at 633 nm. The flowdown (allocation) of this error to other sources in the DCATT system is called the uncorrected error budget. This budget will be elaborated below in the first section. The residual errors, after operation of the DM, must total 1 /4.43 waves. The flowdown (allocation) of this error to other sources in the DCATT system is called the corrected error budget. This budget will be elaborated below in the second section. The values in the uncorrected budget have in most cases been reconciled with estimates of what is achievable by the cognizant engineers. In the other cases they represent the best estimates available. In the last discussion of results section the connection to the design sensitivity analysis will be made. The fabrication specifications and alignment tolerances for the optical elements were developed by connecting the sensitivity analysis to the uncorrected error budget. The wavefront values are taken to represent the largest values within the 4 arcmin full field angle.

The second line of this budget has three entries. These are the following: input, telescope (second pass), and the aft optics. The values for each are shown in the Figure 2:

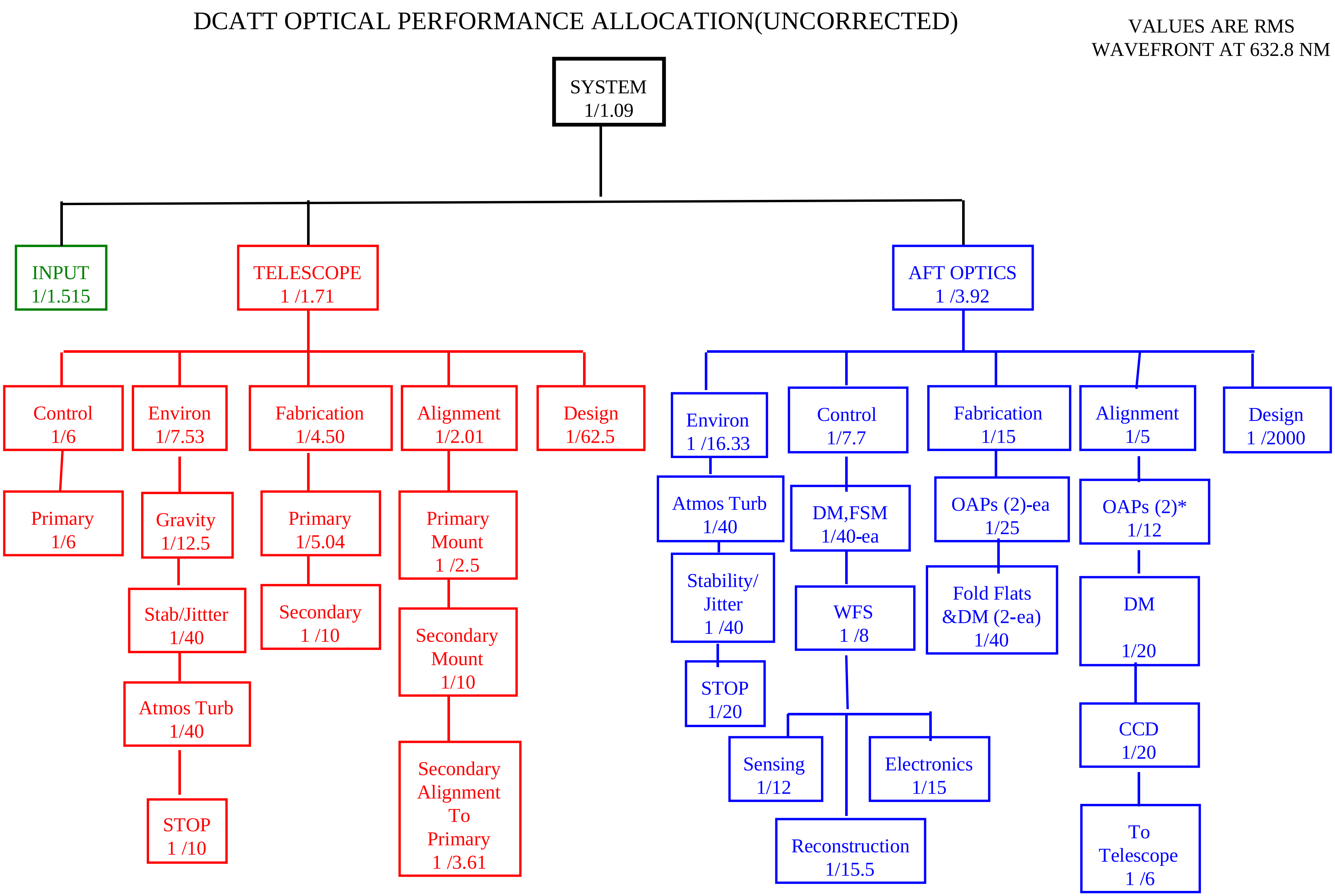

Figure 2. Uncorrected System Error Budget

The input has the largest value because it includes the telescope on the first pass, the A/C flat and the source module. It is noted that rss (root-sum-square) of the second line is 1 /1.09 waves, thus there is a 9% margin. This derived requirement was developed above. It is essentially mid-range for the DM envisioned. Indeed the combination of factors used to arrive at the value in any given box is the RSS of the values connected to that box. All the entries, below the third horizontal row, are displayed in column form (vertically)for compactness. All vertical entries at this lowest level still combine in an RSS fashion.

The telescope budget, on the third line in the figure, is broken into the following entries: control (primary mirror), environmental factors, fabrication, alignment, and design. The values for each are shown in the figure. The environmental factors include these terms: gravity (deformation of primary mirror); stability/jitter; atmospheric turbulence due to the long optical path; and Structural/ Thermal/ Optical effects, which include thermal gradients among other effects. The fabrication of the telescope, at a value of 1 /4.5 waves assures a diffraction limited telescope at 2um, discounting mount and alignment effects and before the DM performs its magic. The flowdown of fabrication errors will be presented later and the connection made to the sensitivity analysis. The alignment of the telescope, the dominant term at 1 /2.01 waves, contains these factors: primary mount effects (actually the difference between the final metrology mount and the actuated mounted), secondary mount effects, and alignment of secondary to primary. The flowdown of alignment errors will be presented later and the connection made to the sensitivity analysis. The last entry under the telescope is the design residual error. The design is well corrected. The primary off axis aberration is coma, introduced by the Cassegrain telescope. There is residual astigmatism and field curvature; the latter is well within the diffraction depth of focus (+/- 0.25 mm).

The AO on the third line in the figure above, are broken into the same entries as the telescope: control, environmental factors, fabrication, alignment, and design. Different lower level factors occur and smaller wavefront aberration values pertain. The environmental factors are the same (although the numbers are smaller) except no appreciable gravity sag occurs. The control factors are significantly different with the crucial factors concerning the DM and Wavefront Sensor coming into play. The Wavefront Sensor factors include the sensing (CCD camera), other electronics (amplifiers, A/D, etc.), and the reconstruction process. The fabrication factors are fairly small with the Off-Axis Parabolas (OAP) dominating the error terms here. Alignment includes several crucial factors: OAP's, DM (really the pupil location error), (CCD) camera alignment, and the critical telescope to AO bench alignment (second pass). The design error is very small.

The input budget includes provision for the actual light source in the source module (including reflection from and transmission through the insertion beamsplitter), the telescope (first pass) and the A/C flat. Alignment of the telescope to the table for this first pass is included in the source module under alignment. This budget is shown below in Figure 3:

DCATT OPTICAL PERFORMANCE ALLOCATION(UNCORRECTED)

VALUES ARE RMS
WAVEFRONT AT 632.8 NM

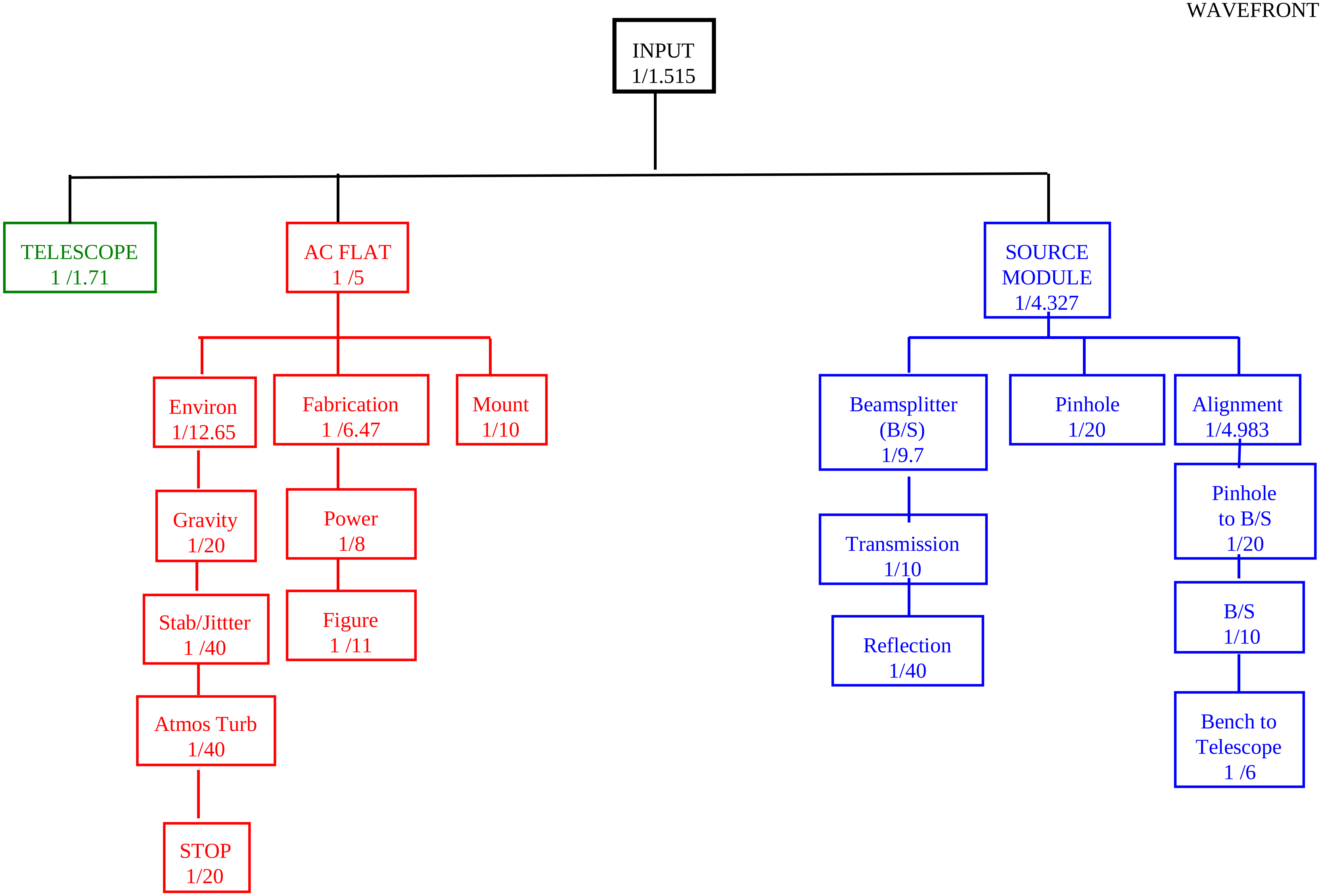

Figure 3. Uncorrected input error budget

No retrace errors are specifically contained in this entire analysis. The presence of such errors and their magnitude is actively under investigation. It is planned to report results later.

The A/C flat exhibits three types of errors: environmental, fabrication, and mount. The total wavefront error allocation is 1/5 wave RMS. The environmental factors are the same as for the telescope with slightly different numerical values. The fabrication errors for the flat are power (non infinite curvature), and figure (irregularity). The mount error actually represents the difference between the final metrology mount and the Hindle mount used in the testbed.

Last but certainly not least are the errors in the source module on the AO bench. The total wavefront error is 1 /4.327 wave RMS. These errors include the effects of reflection from and transmission through the insertion beamsplitter (B/S), the pinhole with its alignment to the actual light source, and key alignment terms. These terms are the following: pinhole to B/S alignment , B/S alignment to the whole system, and the critical telescope to AO bench alignment (first pass).

5. CORRECTED ERROR BUDGET

The corrected error budget includes the same factors as elaborated above. But the values contained in this represent the smaller values achieved as a result of the DM rejecting a portion of the corresponding wavefront errors; that is, the residuals after correction by the DM are given here. In general disturbances with low order aberration coefficient content and substantial error magnitude will be rejected effectively, leaving a small residual. Disturbances with higher order content, smaller error magnitude, or of unknown statistical variation will be less effectively rejected. An example of higher order content would be edge effects. An example of smaller error magnitude would be wavefront errors due to optical flats. Atmospheric turbulence would involve statistical effects.

The corrected system error budget is shown in the Figure 4 .

DCATT OPTICAL PERFORMANCE ALLOCATION (CORRECTED)

VALUES ARE RMS
WAVEFRONT AT 632.8 NM

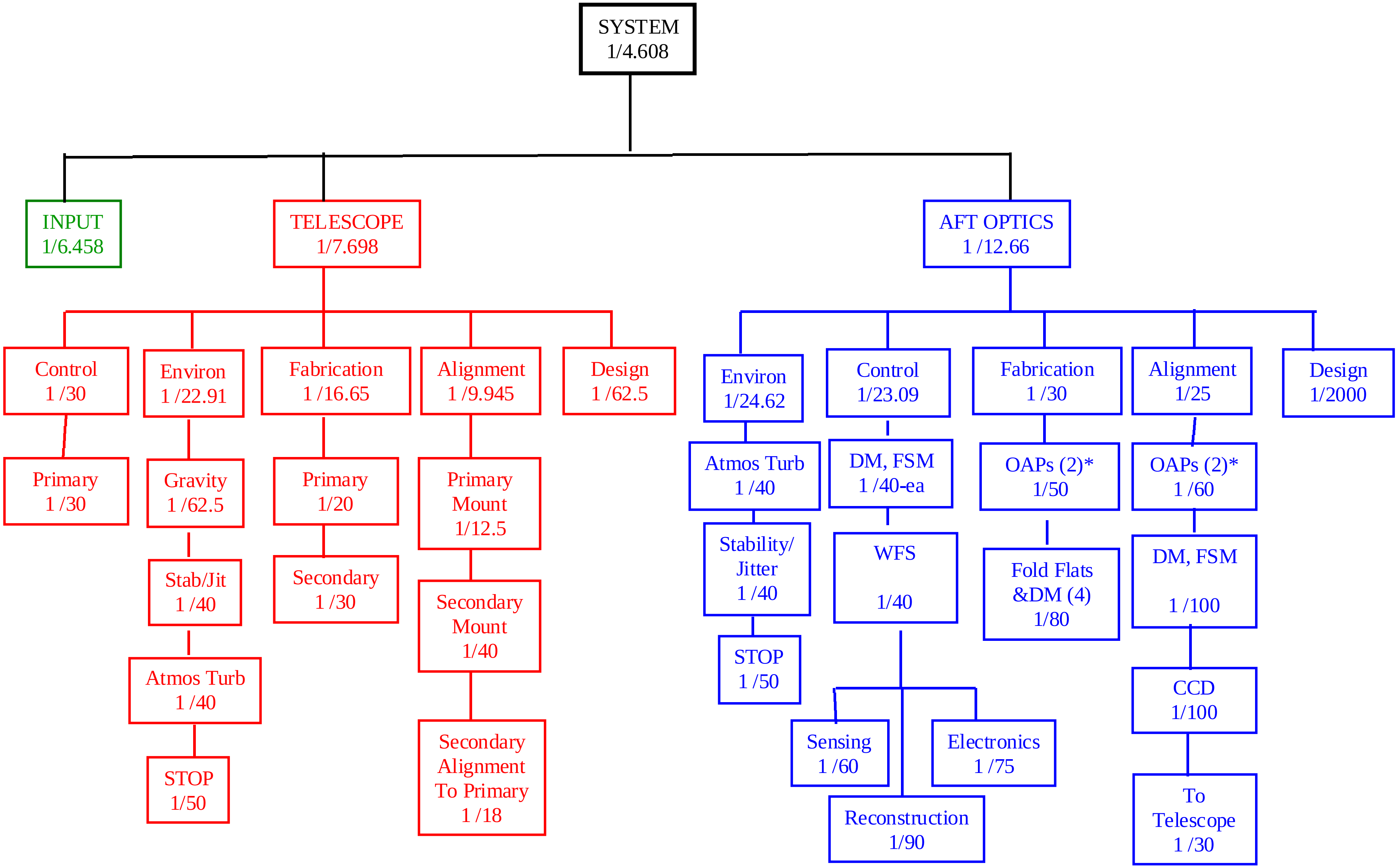

Figure 4. System corrected error budget

It is noted that rss of the second line of the system budget is 1 /4.608 waves, thus there is a 4% margin over the1 /4.43 wave requirement. Indeed the combination of factors used to arrive at the value in any given box is the rss of the values connected to that box, just as in the case of the uncorrected budget. All the entries, below the third horizontal row, are displayed as before and combine in the same RSS fashion.

The telescope budget, on the third line in the figure and with the same entries as before, is 1 /7.698 waves rms. The environmental factors are the same as before. The gravity sag and STOP effects have low order aberration content, thus these errors can be reduced significantly. Whereas the stability/jitter and turbulence effects, which are of an unknown dynamic characteristic cannot be. The fabrication of the telescope, at a value of 1 /16.65 waves, can be significantly reduced, but certain edge effect factors will remain. The alignment of the telescope is as before the dominant term at 1 /9.945 waves. These misalignments introduce predominantly defocus coma, astigmatism, and spherical aberrations. Thus the DM is quite effectively able to attenuate these disturbances. The last entry under the telescope is the design residual error. This error is so small that the DM cannot further correct it.

The AO on the third line in the figure above, are again broken into the same entries as the telescope. Different lower level factors occur and smaller wavefront aberration values pertain. The environmental factors are the same (although the numbers are smaller) except no appreciable gravity sag occurs. As with the telescope environmental factors only the STOP effect can be reduced by the DM. The control factors are significantly different with the crucial factors concerning the DM and Wavefront Sensor coming into play. The Wavefront Sensor factors include the sensing (CCD camera), other electronics (amplifiers, A/D, etc.), and the reconstruction process. The fabrication factors are fairly small with the OAP's dominating the error terms here. These errors can be reduced slightly from the uncorrected case. The alignment errors can be substantially reduced from 1/5 to 1 /25 wave.

The input budget includes provision for the actual light source in the source module (including reflection from and transmission through the insertion beamsplitter), the telescope (first pass) and the A/C flat. The input total is 1 /6.458. Alignment of the telescope to the table for this first pass is included in the source module under alignment. This budget is shown below in Figure 5:

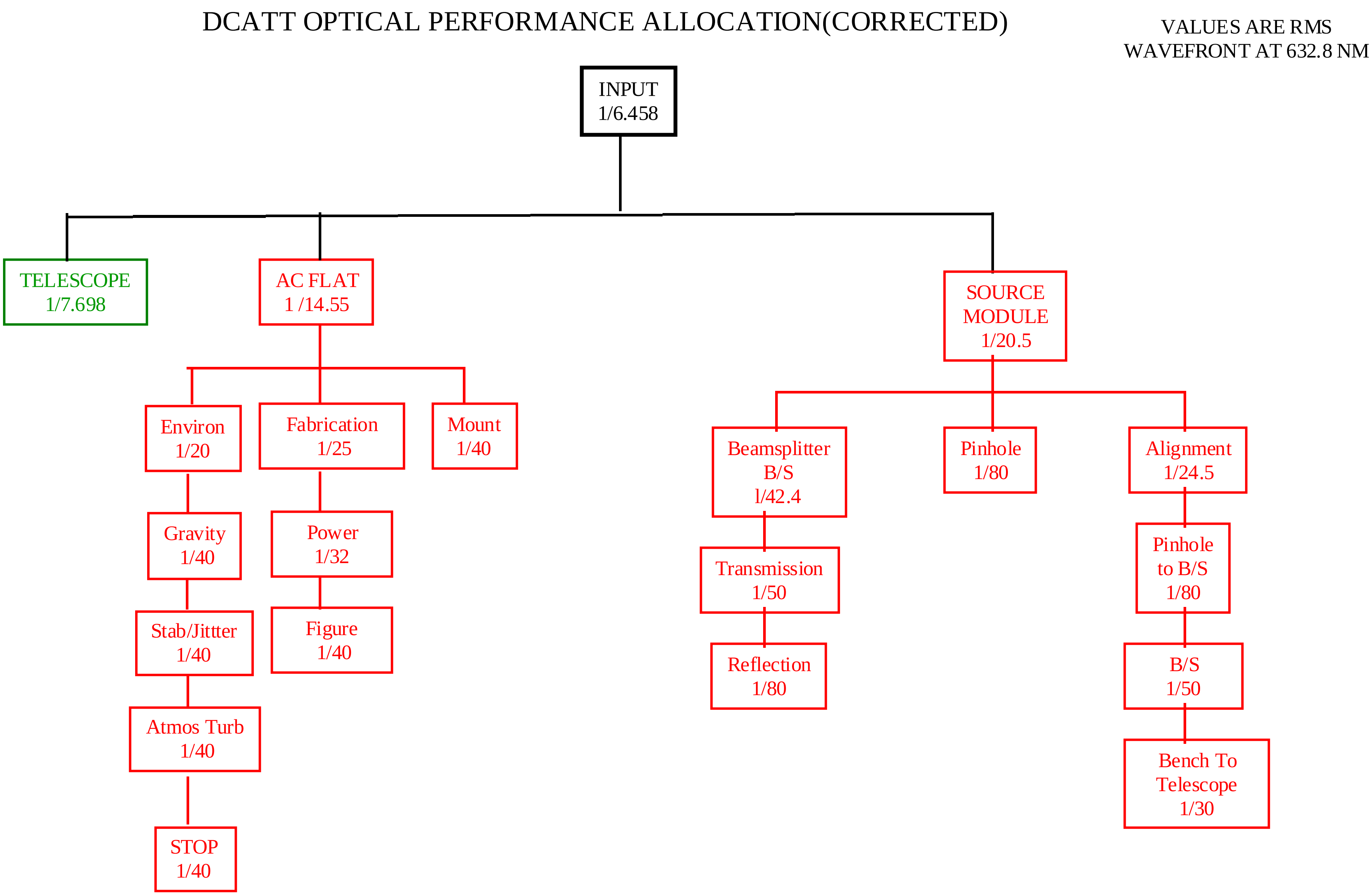

Figure 5 . Corrected input error budget

The remaining A/C flat error is 1 /14.55. The environmental factors are the same as for the telescope with slightly different numerical values. Again, only gravity sag and STOP aberrations can be attenuated and then only slightly since they are relatively small. The fabrication errors for the flat can be effectively rejected leaving only 1/25 wave. The mount errors actually represent the difference between the final metrology mount and the Hindle mount used in the testbed. These errors decrease from 1/10 to 1/40 wave.

Last but certainly not least are the errors in the source module on the AO bench. These errors include the effects of reflection from and transmission through the insertion beamsplitter (B/S), the pinhole with its alignment to the actual light source, and key alignment terms. The total value here is 1 /20.5 waves . The alignment terms can be rejected effectively leaving small residuals.

6. SENSITIVITY ANALYSIS

The approach used here allows fabrication and alignment tolerances to be developed from the uncorrected error budget. To accomplish this an optical analysis software code is used to calculate the wavefront error resulting from given input quantities of a selected system disturbance. For example a radius of curvature mismatch error is selected (indeed a range of values are selected and plotted graphically). The resulting wavefront error is computed (a series actually). The error budget, developed down to the necessary level, will contain the aberration value. The error is then simply read from the graph developed.

Two optical analysis codes have been utilized. One was the Modeling and Analysis for Controlled Optical Systems (MACOS) code, developed at JPL by one of the authors[4]. The other is CODE V[5]. Fabrication and alignment tolerances were developed for the primary mirror and segments, the secondary mirror, and OAP's. Alignment tolerances for the telescope to the AO Bench have been developed. Code V was used for all the elements except the primary segments. MACOS was used for the primary segment tolerances.

A. ESTABLISHMENT OF FABRICATION TOLERANCES

The telescope fabrication tolerances are presented first. It is noted that these error budget values are one level below those presented above in the uncorrected error budget. Fabrication of the elements is driven by the uncorrected system performance! They are shown in Table 1 below. The first column is in inverse waves, the second in fractional waves, and the last is the tolerance.

	1/waves	waves	Tolerance
PRIMARY			
base rad. curv.	10.00	0.1	40mm
radius match-RSS	10.00	0.1	100um
conic k	20.00	0.05	0.001
vertex loc-RSS	10.00	0.1	100um
figure-RSS	12.00	0.083333	
SECONDARY			
rad. curv.	20.00	0.05	3.0mm
conic k	20.00	0.05	0.02
vertex loc	20.00	0.05	70.7um
figure	20.00	0.05	

Table 1. Telescope fabrication tolerances

To determine the base radius and conic constant tolerance, the focus position of the telescope can be adjusted, ie. it is a compensator that is used in the calculation using CODEV. These tolerances are relatively loose and should not represent a difficult challenge for either the primary or the secondary.

The vertex location and radius matching tolerances were calculated for the primary using MACOS. Each is 100um in size for the primary. It is noted that these tolerances for the primary are much more demanding and are critical to the success of the testbed. For the secondary , of course, there is no radius matching since it is monolithic. However the vertex location tolerance for the secondary could also prove demanding at 70.7 um. The fabrication tolerance for the OAP's is 1/25 wave each and was met with off-the-shelf components.

B. ESTABLISHMENT OF ALIGNMENT TOLERANCES

The telescope alignment tolerances are presented first. It is noted that these error budget values are one level below those presented above in the uncorrected error budget. They are shown in Table 2 below:

	1/waves	waves	tolerance
PRIMARY&MOUNT			
Mount Dif	5	0.2	
x-tilt(RSS)	7.07	0.141443	14arcsec
x-decenter(RSS)	7.07	0.141443	140um
y-tilt(RSS)	7.07	0.141443	14arcsec
y-decenter(RSS)	7.07	0.141443	140um
Defocus(RSS)	5	0.2	20um
Secondary Alignment to Primary			
x-tilt	14.14	0.070721	1arcmin
x-decenter	14.14	0.070721	100um
y-tilt	14.14	0.070721	1arcmin
y-decenter	14.14	0.070721	100um
Defocus	4.2	0.238095	16um

Table 2. Telescope alignment tolerances

It is noted that the telescope alignment to the AO bench is treated below. The secondary mount errors are not broken out. The primary and mount tilt and decenter errors are challenging but should be feasible, 14 arc sec and 140um. The defocus(which is synonymous with despace) may prove somewhat more challenging at 20um. The secondary to primary tilt and decenter errors are feasible, 1 arc min and 100um. The defocus(which is synonymous with despace) may prove somewhat more challenging at 16 um. The sensitivity curves are shown in Figure 6, for the primary segments, from which the tolerances are derived as explained above.

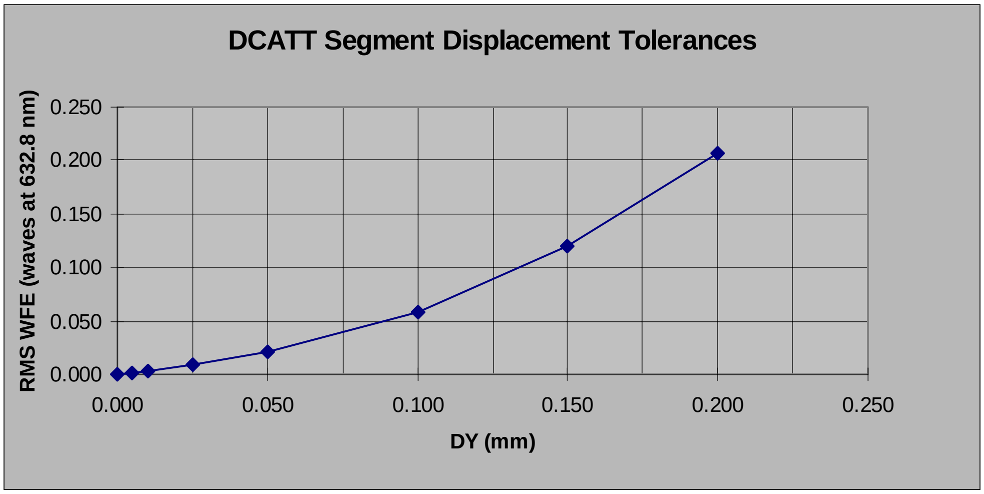

Figure 6. Primary Mirror Alignment Sensitivity

Last , but certainly not least, are the AO bench tolerances, including the crucial telescope to bench alignment factors. Again this Table 3 represents a flowdown from the uncorrected error budget and is shown below:

	1/waves	waves	tolerance
OAP-each	16.32993	0.061237	
Mount Dif	40	0.025	
x-tilt	40	0.025	2arcmin
x-decenter	40	0.025	1mm
y-tilt	40	0.025	2arcmin
y-decenter	40	0.025	1mm
Defocus	40	0.025	1mm
Alignment to Telescope			
x-tilt	20	0.05	4arcmin
x-decenter	20	0.05	2mm
y-tilt	20	0.05	4arcmin
y-decenter	20	0.05	2mm
Defocus	7.5	0.133333	0.5mm

Table 3. AO bench Alignment Tolerances

For each OAP the tilt and decenter errors are should be straightforward to achieve, 2 arc min and 1 mm. The defocus (despace) should also be achievable at 1mm.

The telescope alignment to the AO bench is treated below. The tilt and decenter errors are achievable, 4 arc min and 2mmm. It should be noted, though, that we do have the problem of deciding whether to move the mountain or Mohammed. The defocus(which is synonymous with despace) may prove somewhat more challenging at 0.5 mm.

7. CONCLUSION

In this paper an analysis we have elaborated the performance of the DCATT in carrying out its vital function of wavefront control. The system is geared to be a hardware demonstrator of major NGST functions. We have analyzed the performance of the wavefront control subsystem, before operation of the DM but after initial alignment and course control. The performance after operation of the DM has also been analyzed. The system was described as a function of the following crucial factors: control, environmental, fabrication, alignment, and design.

It is important remember the basis of the analysis. The top line value in the uncorrected error budget is set at mid-range of the DM correction capability. This value serves as the driver for determination of the fabrication specifications and alignment tolerances for the optical elements.

The optical elements for the system have been or are presently being ordered to these specifications. Much more modeling and analysis are planned to obtain greater depth and detail to our predictions of performance. In addition plans are under way to develop as manufactured, assembled, and tested error budgets.

The wavefront reconstruction (using phase retrieval) and DM actuation in the last phase of the optical control experiment for DCATT will take a one wave RMS (@632.8nm) wavefront and reduces it to 1 /4.43 waves RMS or possibly better. This result scales to the system fundamental requirement of diffraction-limited (1 /14 wave)RMS performance at 2 um wavelength for the entire DCATT system.

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